Measuring CP violation in $B_s^0 \to \phi\phi$ with LHCb

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Sensitivity studies to the CP-violating parameters of the decay $B_s^0 \to \phi\phi$ with the LHCb experiment are presented. The decay proceeds via a $b \to ss\bar{s}$ gluonic-penguin quark transition, which is sensitive to contributions from beyond the Standard Model particles. A time-dependent angular analysis of simulated data leads to an expected statistical uncertainty of 6° on any new physics induced CP-violating phase for a sample corresponding to 2 fb^{-1} of integrated luminosity. The expected precision on $\sin 2\beta$ from the related decay $B^0 \to \phi K_S^0$ is also discussed.

I. INTRODUCTION

The amplitude for the decay $B_s^0 \to \phi\phi$ is dominated by gluonic-penguin quark transitions $b \to ss\bar{s}$ (Fig. 1). Gluonic-penguin processes are sensitive to beyond the Standard Model particles that contribute within the loop. The e^+e^- B-factories have measured $\sin 2\beta$ in nine B^0 gluonic penguin decay modes, such as $B^0 \to \phi K_S^0$ and $B^0 \to \eta' K_S^0$ [1]. All the measurements of $\sin 2\beta$ from these modes have values below that measured in $b \to c\bar{c}s$ transitions, but no individual measurement shows a significant deviation.

The decay $B_s^0 \to \phi\phi$ is predicted to have a CP-violating phase less than 1° within the SM [2]. The dependence on V_{ts} in both the mixing and decay amplitudes leads to a cancellation of the B_s^0-mixing phase. Therefore, if any significant CP-violation is measured in $B_s^0 \to \phi\phi$ decays it is an unambiguous signature of new physics. The decay is of a pseudoscalar meson to two vector mesons, which leads to the final state being a CP-even and CP-odd admixture. Therefore, a time-dependent angular analysis is required to extract the CP-violating parameters of the decay.

The paper is organized as follows. Section II contains a brief description of the LHCb experiment. The predicted event yields and background estimations are described in Section III. The CP sensitivity study is presented in Section IV. The LHCb prospects with the related mode $B^0 \to \phi K_S^0$ are discussed in Section V. The conclusions are given in Section VI.

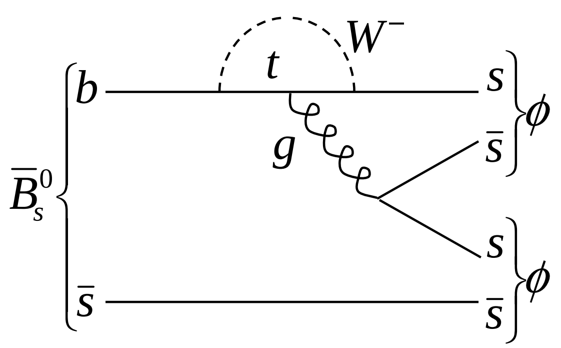

FIG. 1: The main diagram contributing to the decay $B_s^0 \to \phi\phi$.

II. THE LHCb EXPERIMENT

The Large Hadron Collider (LHC) collides protons at a centre-of-mass energy of 14 TeV. The LHC produces 10^{12} $b\bar{b}$ quark pairs per nominal year of data-taking (10^7 s) when operating at an instantaneous luminosity of 2×10^{32} cm^{-2}s^{-1}.[1] The LHCb spectrometer [3, 4] instruments one forward region about the pp collision point. The forward geometry captures approximately one-third of all B hadrons produced and increases the probability of both B hadrons from the $b\bar{b}$ pairs being within the acceptance, which improves the efficiency of flavour tagging.

A silicon vertex detector, with sensors perpendicular to the beam axis, is situated close to the interaction region in a secondary vacuum. The detector provides accurate determination of primary and secondary vertices leading to a proper-time resolutions of approximately 40 fs in hadronic B-decays such as $B_s^0 \to \phi\phi$. Tracking stations either side of a 1.2 T dipole magnet produce momentum measurements with an accuracy of a few parts per mille. There are two Ring-Imaging Čerenkov detectors, with 3 different radiators, that allow identification of $K^\pm$ from $\pi^\pm$ over the momentum range 1 to 100 GeV/c.

In addition, the detector includes an electromagnetic calorimeter, a hadron calorimeter and a muon detector. These components are critical for identifying large transverse momentum, p_T, electrons, photons, hadrons and muons from B-hadron decay in the initial hardware stage (Level-0) of the LHCb trigger. The Level-0 trigger reduces the 40 MHz collision rate to 1 MHz. All data is then transferred from the detector to a dedicated CPU farm where the Higher Level Trigger (HLT) algorithms are performed. Initially an association between the high

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[1] This luminosity optimises the number of single interactions per bunch crossing.

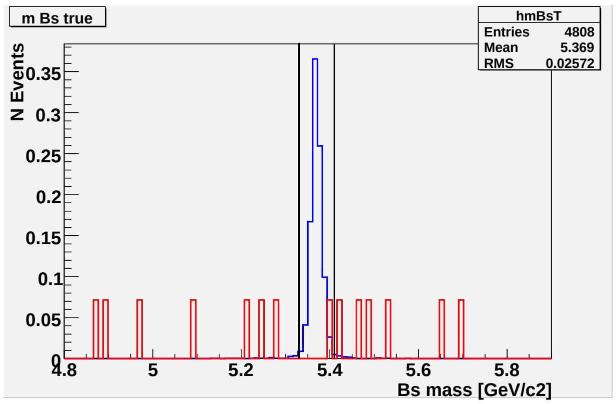

FIG. 2: The B_s^0 mass of candidates reconstructed in the signal (blue) and inclusive $b\bar{b}$ simulation samples (red) before trigger selections. The normalisations are arbitrary.

p_T objects that satisfy the Level-0 trigger and tracks with large impact parameter to the primary vertex is sought. If this is successful, exclusive and inclusive HLT algorithms are executed resulting in a 2 kHz output rate to disk.

III. EVENT SELECTION AND BACKGROUND ESTIMATION

The estimation of $B_s^0 \to \phi\phi$ yields and background has been performed on simulated data. The simulation of the pp collisions and subsequent hadronisation is performed by the `PYTHIA` generator [5]. The decay of any B hadrons produced is simulated by `EVTGEN` [6] and the detector response is performed by `GEANT4` [7]. The resulting data are processed by the complete LHCb reconstruction software. A dedicated sample containing events with a $B_s^0 \to \phi\phi$ decay is used to evaluate the selection efficiency. Minimum bias events are selected rarely by the Level-0 trigger and the HLT. Therefore, an inclusive sample of 34 million events containing $b\bar{b}$ quark pairs is used to estimate the background. Due to the very large number of $b\bar{b}$ pairs that will be produced at LHCb, the inclusive $b\bar{b}$ sample only corresponds to approximately 15 minutes of data taking at the nominal instantaneous luminosity; this leads to large uncertainties on the background estimates.

The selection process begins with the identification of ϕ candidates reconstructed from two oppositely charged kaons. Particle identification and p_T requirements are placed on the $K^{\pm}$ and they must be consistent with production at a common vertex. The mass of the K^+K^- must be within 20 MeV/c^2 of the ϕ mass; the mass interval corresponds to approximately $\pm 3\sigma_{m_\phi}$, where σ_{m_ϕ} is the mass resolution.

B-meson candidates are reconstructed in events with two or more ϕ candidates with a $p_T > 1.2$ GeV/c^2. The B-meson candidates must be consistent with production at a common vertex and this vertex must be well separated from the primary vertex. The B_s^0 candidate mass distribution is shown in Fig. 2 for signal and background samples. Events within 40 MeV/c^2 of the B_s^0 mass are considered as signal; the mass interval corresponds to approximately $\pm 3\sigma_{m_B}$, where σ_{m_B} is the mass resolution. Once Level-0 and HLT trigger selections have been applied there are 4000 signal events expected in every 2 fb^{-1} of integrated luminosity, which corresponds to one nominal year of LHC operation. The event yield is calculated assuming the measured branching fraction $\mathcal{B}(B_s^0 \to \phi\phi) = (14^{+6}_{-5}(stat.) \pm 6(syst.)) \times 10^{-6}$ [8]; the measured value lies within theoretically predicted range [9, 10]. The background remaining in the $b\bar{b}$ inclusive simulation sample is found to consist of combinatoric B_s^0 candidates. The background-to-signal ratio is bounded to lie between 0.4 to 2.1 at the 90% confidence level, with a central value of 0.9.

IV. $B_s^0 \to \phi\phi$ CP SENSITIVITY

The magnitude of any new physics induced CP-phase, ϕ_{NP}, is extracted from a time-dependent analysis of the differential cross section with respect to the three transversity angles defined in Fig 3. The amplitude for the decay can be written in terms of three helicity amplitudes $H_\lambda(t)$ where $\lambda = 0, \pm 1$. The helicity amplitudes are related to the transversity basis by $A_0(t) = H_0(t)$, $A_{||}(t) = \frac{1}{\sqrt{2}}(H_{+1} + H_{-1})$ and $A_{\perp}(t) = \frac{1}{\sqrt{2}}(H_{+1} - H_{-1})$. The amplitudes A_0 and $A_{||}$ are CP even and $A_{\perp}$ is CP odd. The differential cross section is then given by:

$$\begin{aligned}\frac{d\Gamma(t)}{d\chi d\cos\theta_1 d\cos\theta_2} &= |A_0(t)|^2 f_1(\chi,\theta_1,\theta_2)|A_{||}(t)|^2 f_2(\chi,\theta_1,\theta_2) + |A_{\perp}(t)|^2 f_3(\chi,\theta_1,\theta_2) \\ &+ \Im(A_0^*(t)A_{\perp}(t)) f_4(\chi,\theta_1,\theta_2) + \Re(A_0^*(t)A_{||}(t)) f_5(\chi,\theta_1,\theta_2) + \Im(A_{||}^*(t)A_{\perp}(t)) f_6(\chi,\theta_1,\theta_2) \quad (1),\end{aligned}$$

where f_i ($i = 1-6$) are even angular functions as required by Bose symmetry [11]. The time-dependent factors of these angular functions are sensitive to any CP-violating phase. In principle the CP-violating phase can

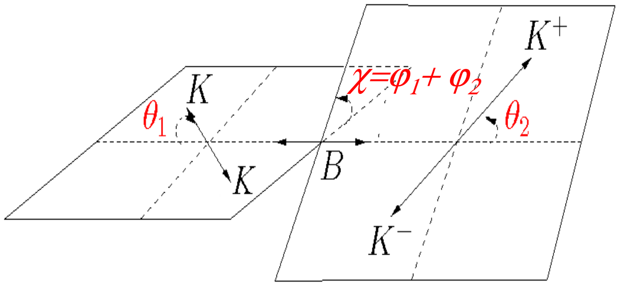

FIG. 3: A schematic of the definition of the transversity angles θ_1, θ_2 and χ.

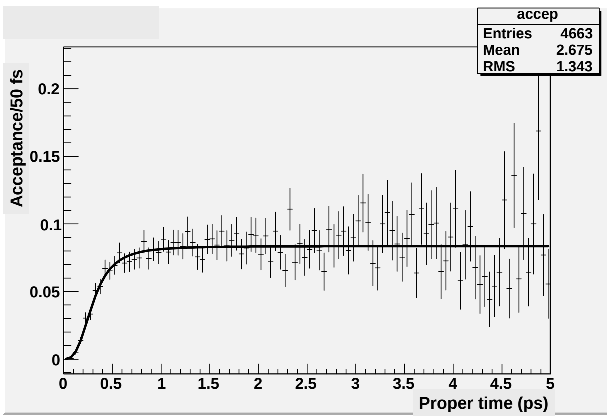

FIG. 4: The variation of the acceptance as a function of the proper-time, τ. The acceptance function fit to the simulated data is $\epsilon(\tau) = \frac{0.084\tau^3}{0.027+\tau^3}$.

be different between the three transversity amplitudes. However, to simplify the analysis it has been assumed to be equal. Significant fine-tuning of the phases would be required for no effects to be observed if new physics induced phases are present. The time-dependent terms also depend on the strong phase differences $\delta_{||,0}$ between $A(t)_\perp$ and $A(t)_{||,0}$, the relative magnitudes of the three amplitudes and the mass (lifetime) differences between the B_s^0 mass eigenstates, Δm_s ($\Delta\Gamma_s$).

Simulated data are generated to follow the differential distribution given in Eqn. 1 with the value of ϕ_{NP} chosen to be 0.2 rad. The strong phases are assumed to be $\delta_{||} = 0$ and $\delta_0 = \pi$; these values are motivated by naïve factorization [12]. The magnitudes of the transversity amplitudes are set to the values measured in the analogous channel for B^0 decays $B^0 \to K^*\phi$ [13, 14]. The value of Δm_s is taken to be 17 ps^{-1} [15] and $\Delta\Gamma_s/\Gamma$ is set to be 0.15, compatible with current experimental constraints [16] and theoretical expectations [17]. The signal sample size has a mean of 4000 events corresponding to an integrated luminosity of 2 fb^{-1}.

The following experimental effects are also simulated.

- The **background** is assumed to be at level 90% of the signal with flat transversity angle and mass distributions, and an exponential lifetime distributions.

- The **tagging power**, $\epsilon(1-2\omega)$, where ϵ is the tagging efficiency and ω is the mistag rate, is assumed to be 9% which has been found in simulation studies of other B_s^0 hadronic decays [18]. This is significantly better than that for B^0 modes because the kaon associated with the B_s^0 hadronisation is also used.

- The **proper-time acceptance** measured from the signal simulation sample is shown in Fig. 4. The reduced acceptance for short lifetimes is the result of trigger and selection requirements on the impact parameters of the B daughters.

- The **proper time and $\mathbf{B_s^0}$ mass resolutions** are estimated to be 40 fs and 12 MeV/c^2, respectively. These resolutions are estimated from the signal simulation sample used for the selection studies.

- The **angular acceptance** and **resolution** are assumed to be flat and to have negligible effect, respectively; this assumption is motivated by the studies of related channel $B_s^0 \to J\psi\phi$ [19].

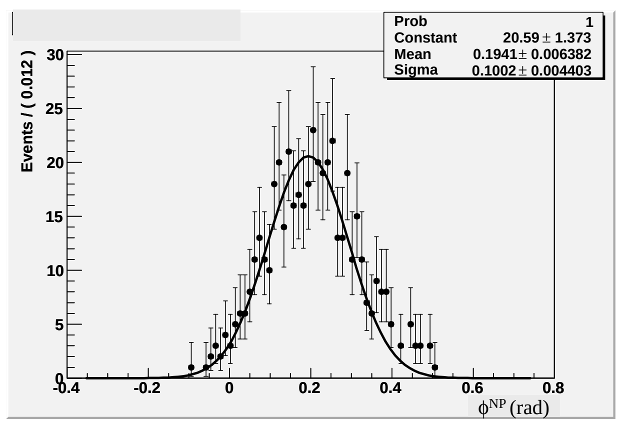

FIG. 5: The distribution of fitted value of ϕ_{NP} for 500 simulated $B_s^0 \to \phi\phi$ experiments.

Five-hundred samples of signal and background events are generated and a maximum likelihood fit is performed on each one. The parameters ϕ_{NP}, $\delta_{||}$, δ_0 and the magnitude of the transversity amplitudes are extracted from the fit; all other parameters are fixed. The distribution of the fitted value of ϕ_{NP} for these 500 experiments is shown in Fig 5. The average error on ϕ_{NP} is 0.1 rad (5.7°). The pull distribution of the true value subtracted from the fitted value divided by the uncertainty is normal.

Sets of 500 experiments are produced varying the input parameters assumed. The variation of the uncertainty on ϕ_{NP} as a function of the $\mathcal{B}(B_s^0 \to \phi\phi)$, signal-to-background ratio and $\Delta\Gamma_s/\Gamma_s$ is given in Table I. The variation of the assumed $\mathcal{B}$ leads to the expected statistical scaling of the uncertainty. The uncertainty on ϕ_{NP} is not degraded significantly until the background-to-signal

TABLE I: The variation of the uncertainty on ϕ_{NP} as a function of the branching fraction, background-to-signal ratio (B/S) and $\Delta\Gamma_s/\Gamma_s$.

$\mathcal{B}$ ($\times 10^{-5}$)	$\sigma(\phi_{NP})$
0.35	13°
0.7	8.1°
1.4	5.7°
2.1	4.6°
B/S	$\sigma(\phi_{NP})$
0	5.5°
0.9	5.7°
2	6.1°
5	7.2°
$\Delta\Gamma_s/\Gamma_s$	$\sigma(\phi_{NP})$
0.05	7.2°
0.15	5.7°
0.05	4.9°

ratio is greater than three. Increasing the value of $\Delta\Gamma_s/\Gamma$ leads to a reduction in the uncertainty because enhanced interference from the lifetime difference among the amplitudes increases the sensitivity to ϕ_{NP}. The values of ϕ_{NP}, the proper-time resolution and the relative magnitudes of the transversity amplitudes are also varied; all these had negligible effect on the sensitivity to ϕ_{NP}.

V. $B^0 \to \phi K^0_S$ CP SENSITIVITY

Simulation studies of the decay $B^0 \to \phi K^0_S$ have also been performed. The expected yield per 2 fb^{-1} of integrated luminosity is 800 events. These yields do not include K^0_S daughters without measurements in the silicon vertex detector, approximately two-thirds of K^0_S from these decays, which are not reconstructed in the current HLT algorithms. Algorithms to perform this reconstruction are currently being developed. The background-to-signal ratio is estimated to be 2.4 from the $b\bar{b}$ inclusive simulation.

A time-dependent analysis of the $B^0 \to \phi K^0_S$ is required to extract the sensitivity to $\sin 2\beta$. A toy simulation study is performed to extract the sensitivity to $\sin 2\beta$. The tagging power is assumed to be 5% and the proper-time resolution is taken to be 60 fs from the simulated signal sample. A 10% K^+K^- S-wave contribution is also included in the fit. The uncertainty on $\sin 2\beta$ is expected to be 0.32 for a data sample corresponding to 2 fb^{-1} of integrated luminosity.

VI. CONCLUSIONS

Sensitivity studies to CP-violation in the decay $B^0_s \to \phi\phi$ have been presented. A sample of data corresponding to an integrated luminosity of 2 fb^{-1} gives an uncertainty of 6° on any new physics induced CP phase. Varying the assumptions used within reasonable ranges changes the predicted statistical uncertainty between 4° and 13°. The largest statistical uncertainty results from decreasing the branching fraction by a factor of four. The measurement of $\sin 2\beta$ from the $B^0 \to \phi K^0_S$ has also been investigated. The sensitivity is expected to be 0.32 with a data set corresponding to 2 fb^{-1} of integrated luminosity; this is of the same order as the current sensitivity of the e^+e^- B-factories [20, 21]. Therefore, in conclusion, $B^0_s \to \phi\phi$ is the most sensitive mode with which to study gluonic-penguin B decays with LHCb.

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